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PROPAGATION OF BOUNDARY AND GEOMETRICAL UNCERTAINTIES FOR THE AEROACOUSTICS ANALYSIS OF A SIDE MIRROR

E. Minisci

Intelligent Computational Engineering Laboratory - Department of Mechanical & Aerospace Engineering, University of Strathclyde, Glasgow, UK

A. Scardigli, F. Gallizio

Optimad engineering S.r.l. - Turin, Italy

In collaboration with

Automobili Lamborghini S.p.A.

Uncertainty Handling

Despite the stochastic nature of aeroacoustics systems and models, non-deterministic investigations in regards to computational aeroacoustics are limited

Sources of Uncertainties

Numerical Analyses

- physical properties of materials and inevitable randomness in boundary conditions and geometries, as well as models uncertainties

Experimental tests

- randomness in boundary conditions

Uncertainties for Numerical Analyses

- Monte Carlo (MC) approach on acoustic signals too slow and too expensive
- **non-intrusive methods** consider the models as black-box and sample it through the use of **meta-modelling** techniques

Work and Objectives

- A **non-intrusive** approach for probabilistic propagation of uncertainties is presented
- Considering boundary and geometrical uncertainties for the aeroacoustics analysis
- Obtained results are used to detail some approaches giving statistical similitude between uncertain numerical performance and (**synthetic**) uncertain experimental data.

Aim

- Show how the appropriate handling of involved **uncertainties** can bring to a better understanding of experimental and numerical modelling and testing, and, consequently, **more efficient design processes**

General Approach

Aeroacoustic loads prediction through CFD simulation

Geometrical model → **Steady-state RANS simulation** → **Transient compressible DES/LES simulation** → **Data analysis**

Geometrical model

Geometry pre-processing

- surface preparation (e.g. cleaning, simplification, introduction of sealing tape)

Mesh generation

- initial guess for surface and volume refinements (tuned after steady-state simulation)

Steady-state RANS simulation

Broadband noise source analysis

- surface and volume indicators (e.g. Curle, Proudman), to determine where the mesh should be refined
- **mesh frequency cut-off** indicator, to determine a spatial resolution capable to capture the frequencies of interest

Flow initialization for transient computations

Transient compressible DES/LES simulation

Compressible turbulent solver to capture

- the propagation of **sound waves**
- the interactions between hydrodynamic and acoustic fields

Data analysis

Sound pressure level analysis

- post-processing of **statistically-steady** signals
- extraction of **acoustic spectra** for further investigations (e.g. SEA analysis)

Comparison between ***numerical*** and ***experimental data***

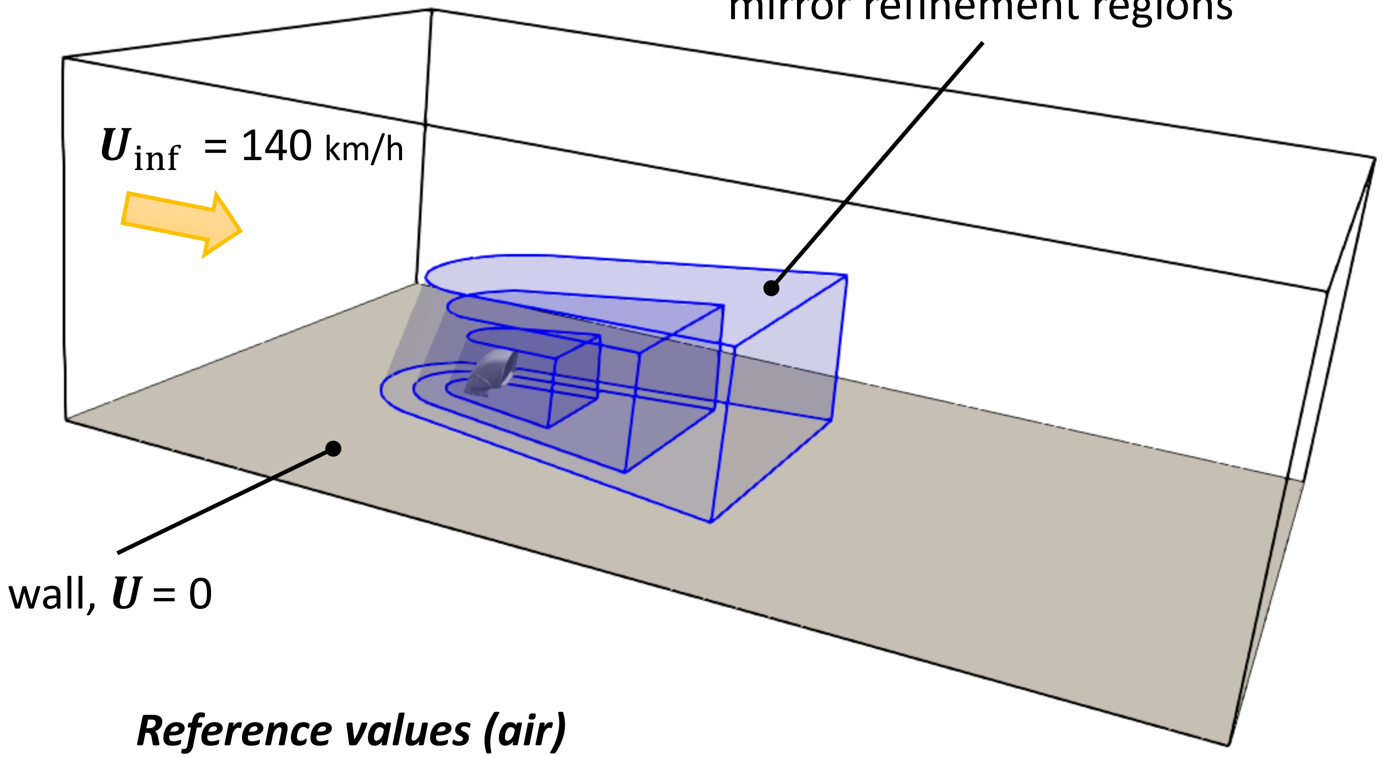
Test case

side-view mirror of LAMBORGHINI URUS

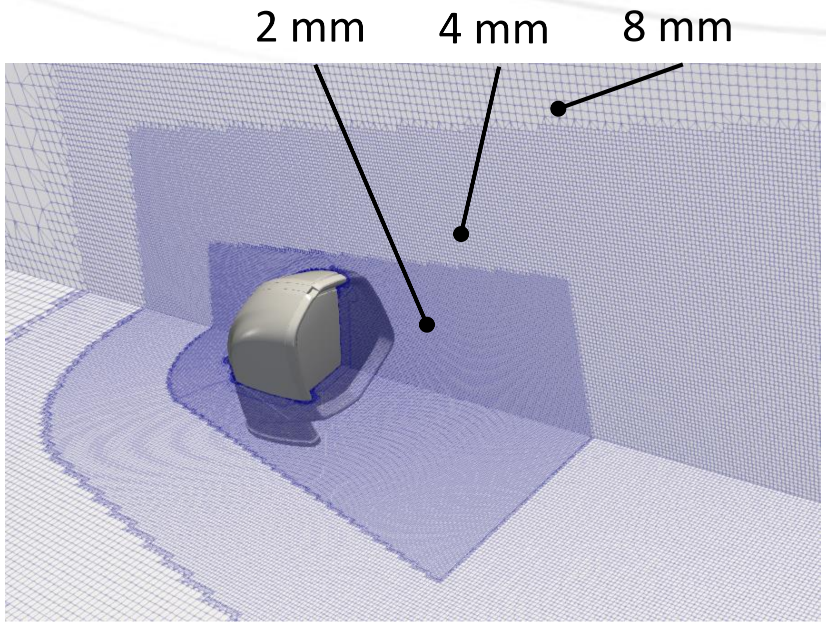
geometrical model courtesy of Automobili Lamborghini S.p.A.

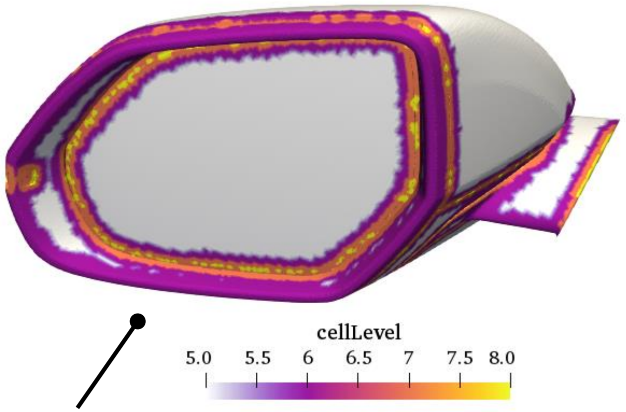
Test case

Numerical setup



Trimmed grid of ~17.5e6 cells





0.125 mm ≤ grid resolution ≤ 1 mm

Reference values (air)

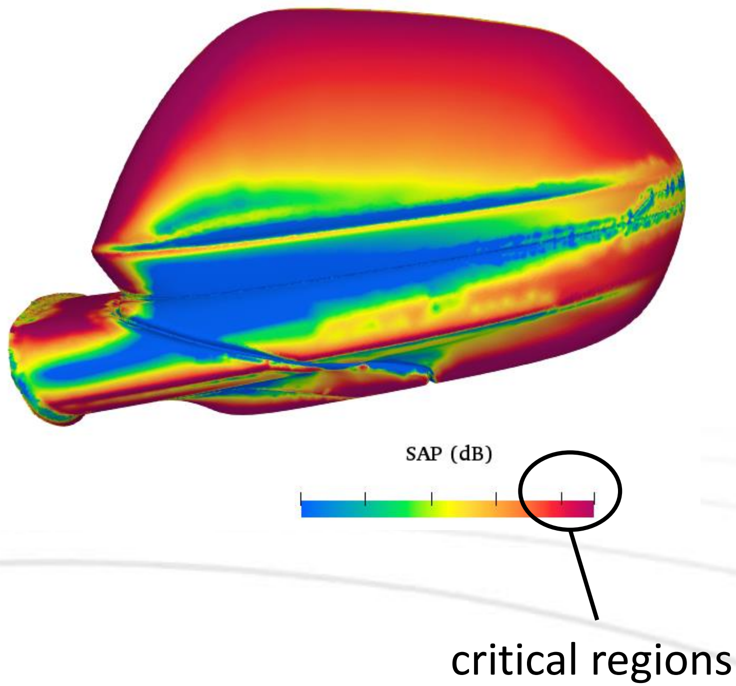
temperature	[°C]	25
pressure	[Pa]	101325
density	[kg/m3]	1.205
kinematic viscosity	[m2/s]	1.516e-05

Steady-state simulation results

Broadband noise sources

Curle Surface Acoustic Power (dB)
Sound generated by dipole sources
→ noise level that the turbulent boundary layer emits over a surface

Proudman Acoustic Power (dB)
Local contribution of quadrupole sources
→ acoustic power per unit volume as emitted by the turbulence structures in the flow field



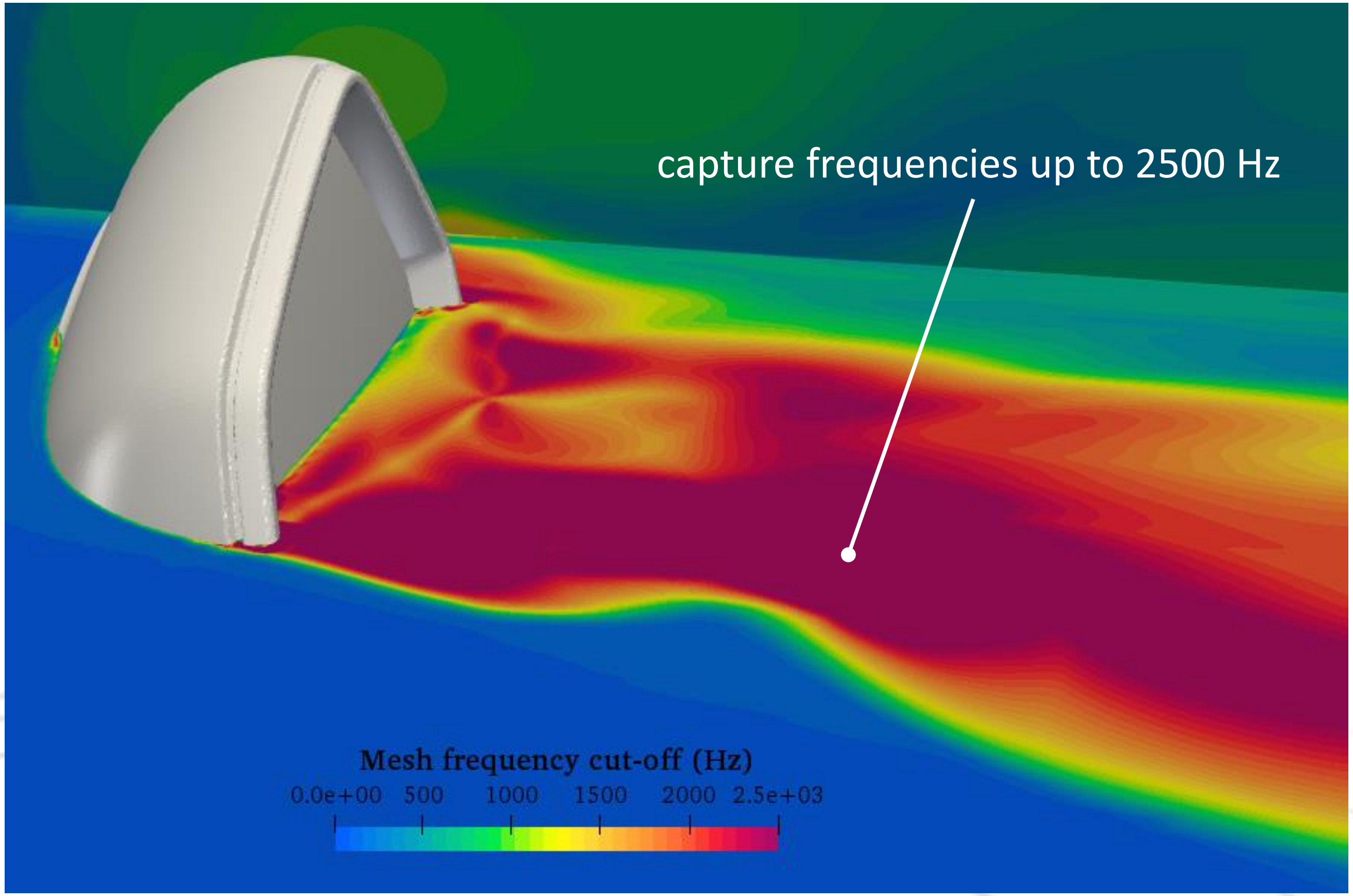
isovolume AP (dB) > AP_{ref}

Steady-state simulation results

Mesh frequency cut-off

Correlation between mesh size and turbulence frequency
→ estimate of the frequencies resolved by the mesh in transient simulation

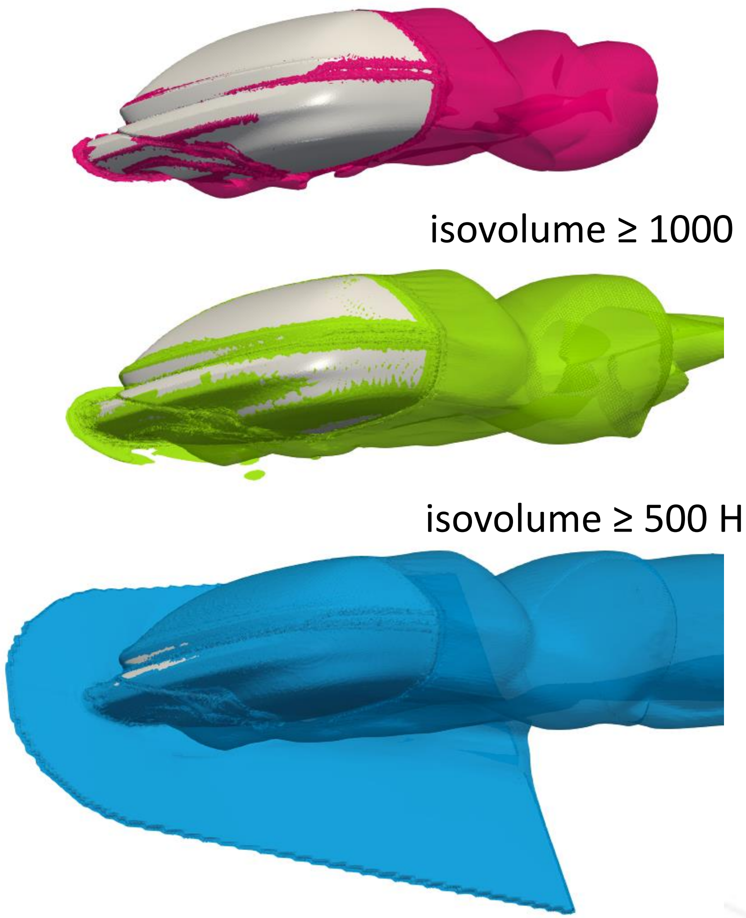
$$f_{MC} = \frac{\sqrt{\frac{2}{3}k}}{2\Delta}$$



isovolume ≥ 2000 Hz

isovolume ≥ 1000 Hz

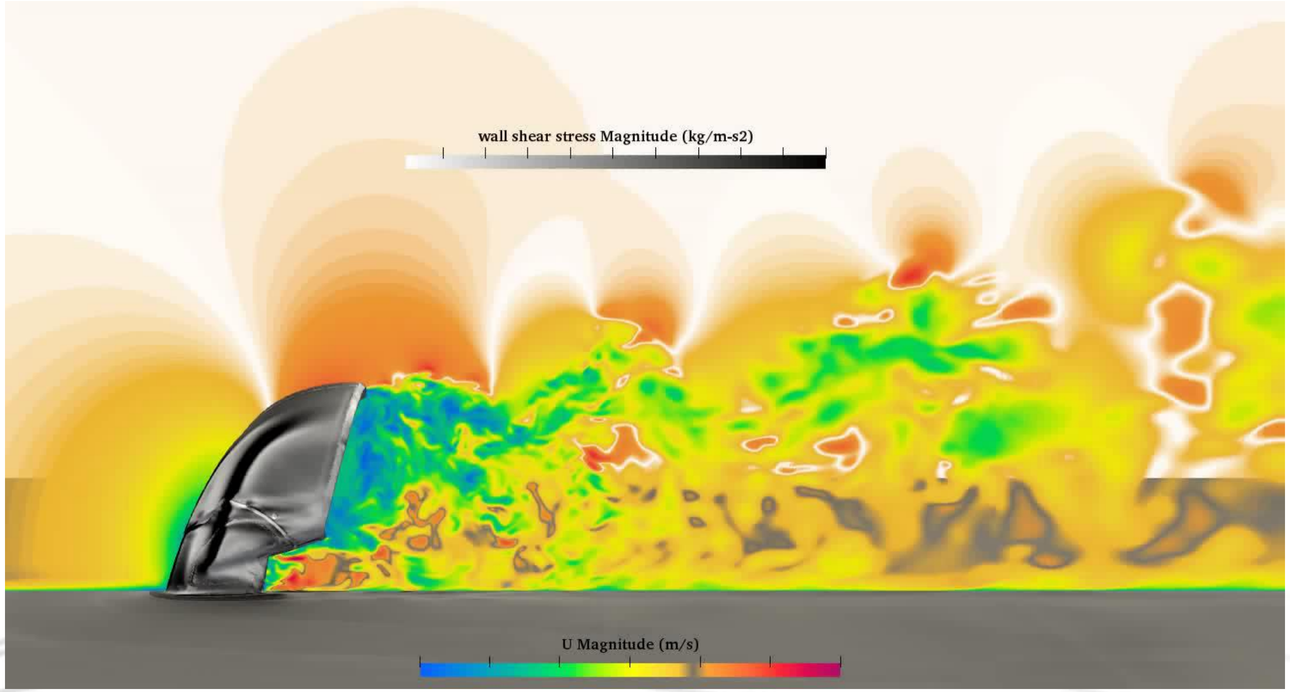
isovolume ≥ 500 Hz



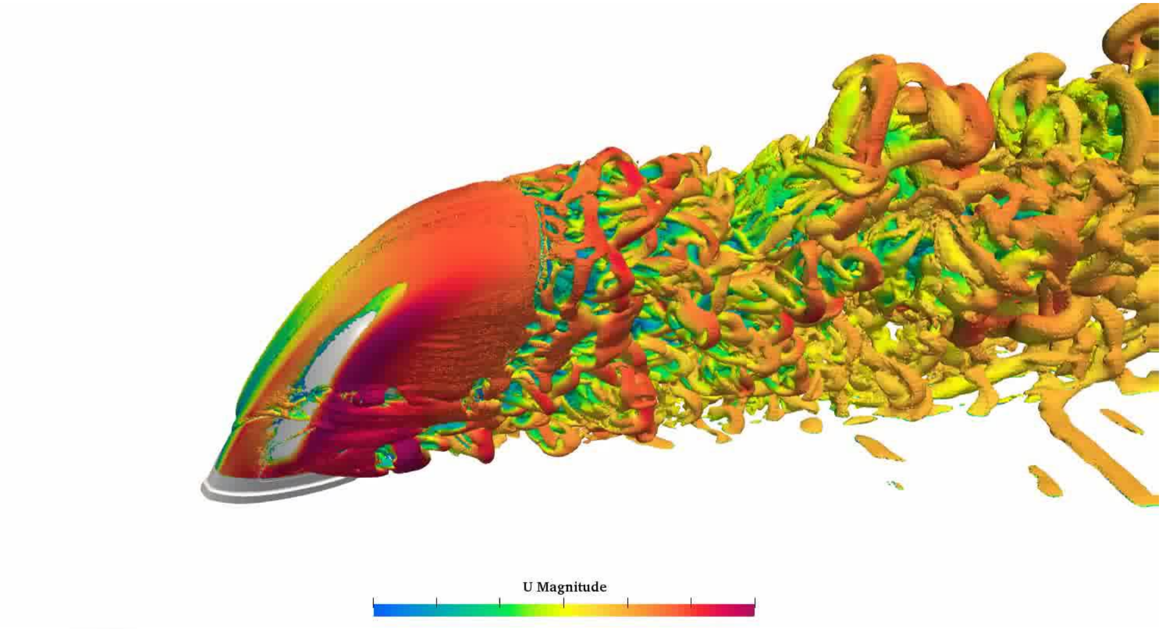
Transient simulation results

Compressible Detached Eddy Simulation (DES), with SST k-ω DDES turbulence model

- 2^{nd} order accurate in space and time
- acoustic damping to avoid reflecting waves on boundaries
- $dt = \frac{1}{16\, f_{\max}} = 2.5e-5$ s, with $f_{\max} = 2500$ Hz



$\boldsymbol{U}_{\text{inf}}$



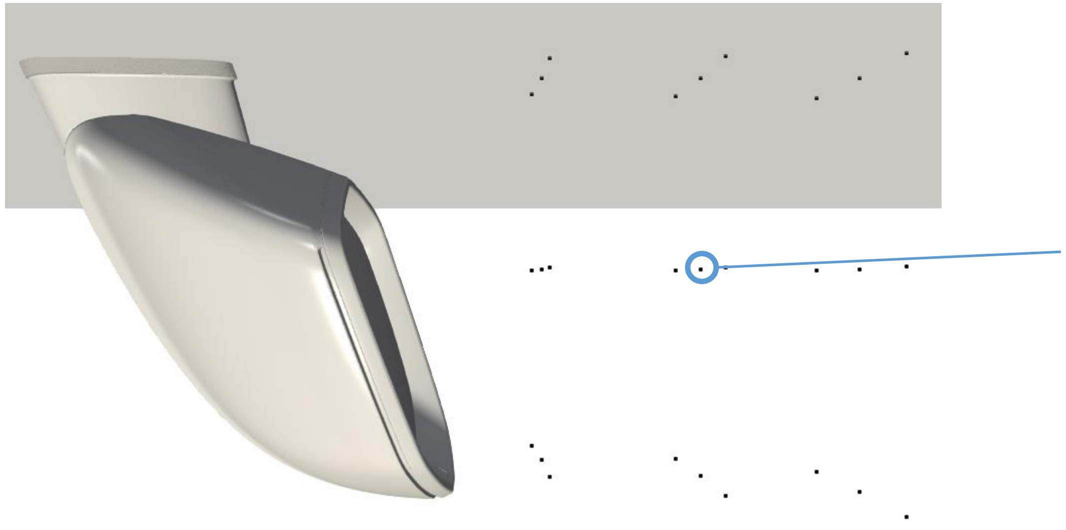
Q-criterion for the identification of vortical structures

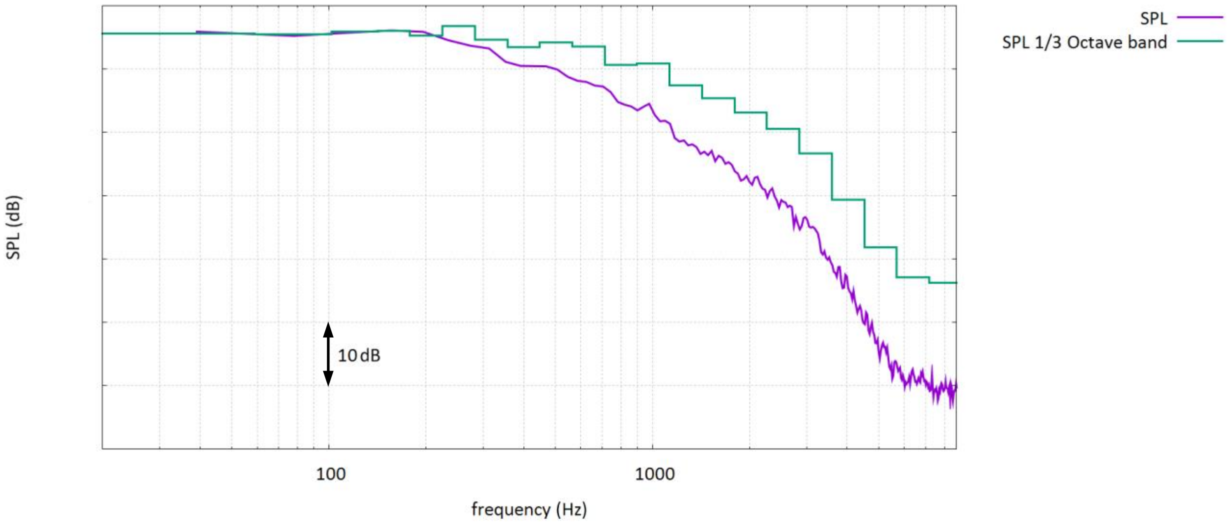
$Q > 0 \rightarrow$ regions where the vorticity magnitude is greater than the strain-rate

Transient simulation results

Sound Pressure Level analysis

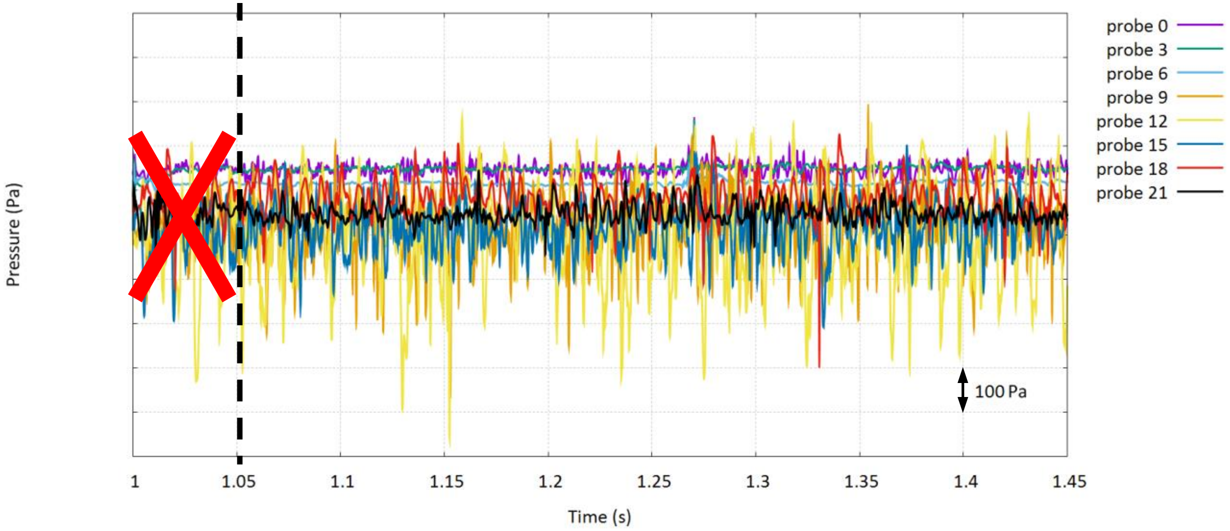
Array of pressure probes distributed in the near wake region and on the wall surface





- simulated time: 0.45 s
- acquisition time: 0.4 s

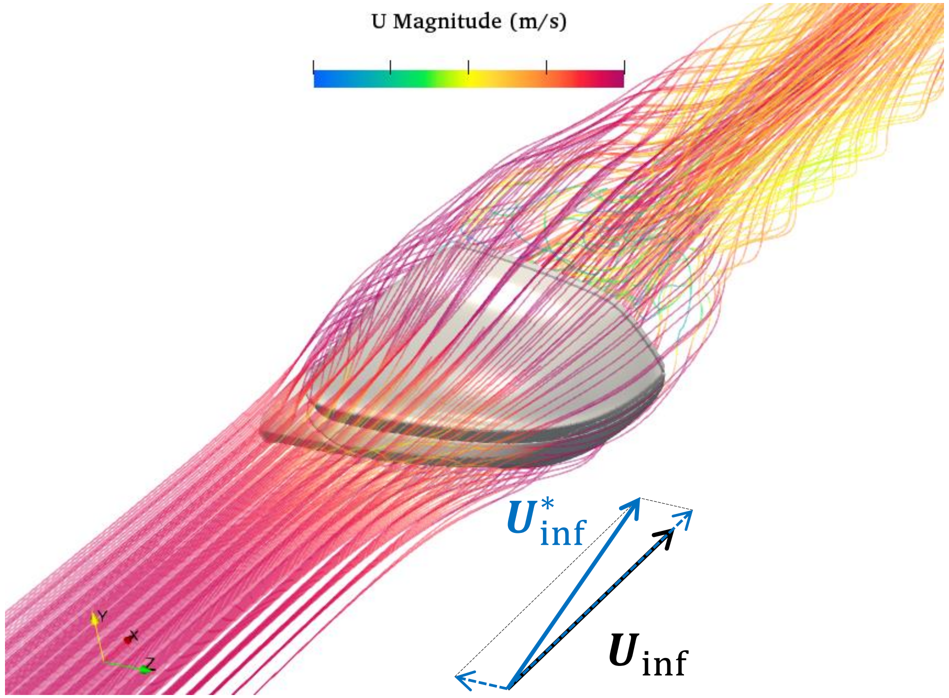
→ the start-up of the simulation is disregarded, in order to process only the ***statistically-steady*** pressure signals



Uncertainties

Uncertainty in the design and operation of engineering systems

→ various sources: materials properties, ***boundary conditions***, ***geometries***, physical models, etc.

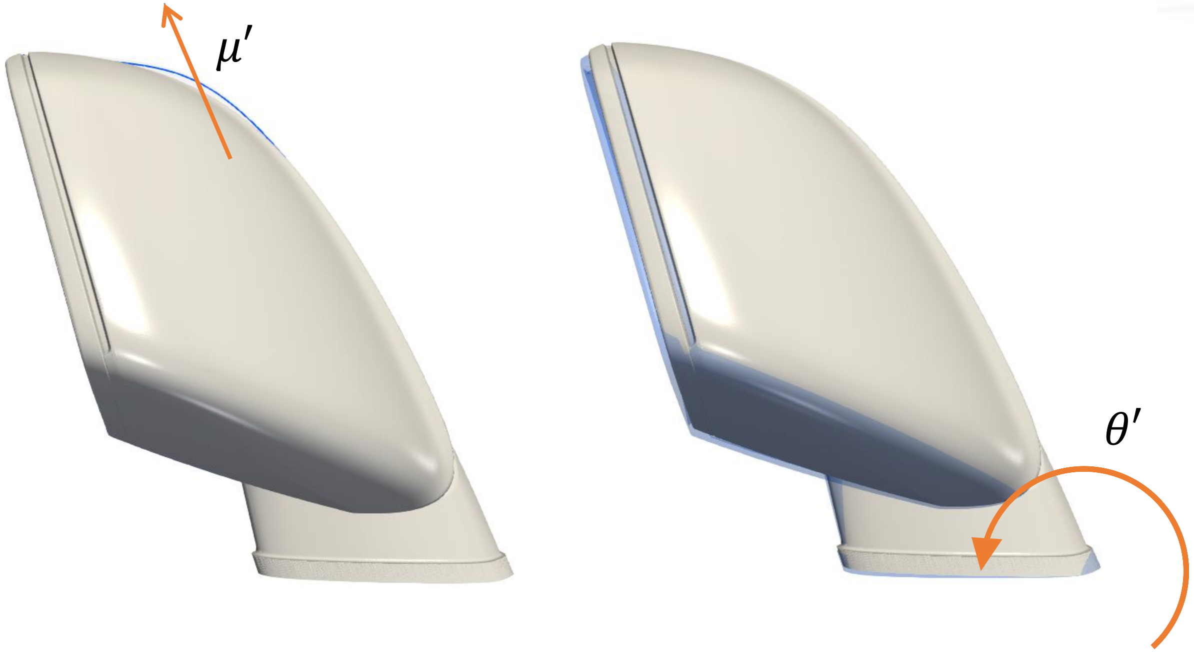


uncertainties in the **magnitude** and **direction** of the far field velocity vector (e.g. lateral wind, nominal speed may differ from its measured value)

$$\boldsymbol{U}^*_{\text{inf}} = (U_{\text{inf}} + u')\boldsymbol{e_x} + w'\,\boldsymbol{e_z}$$

- u' in $[-0.05\ U_{\text{inf}}, +0.05\ U_{\text{inf}}]$
- w' in $[-10$ km/h, $0]$

2 parameters



uncertainties in the **shape** of the mirror or in its **position** (e.g. CAD model/manufactured model discrepancies)

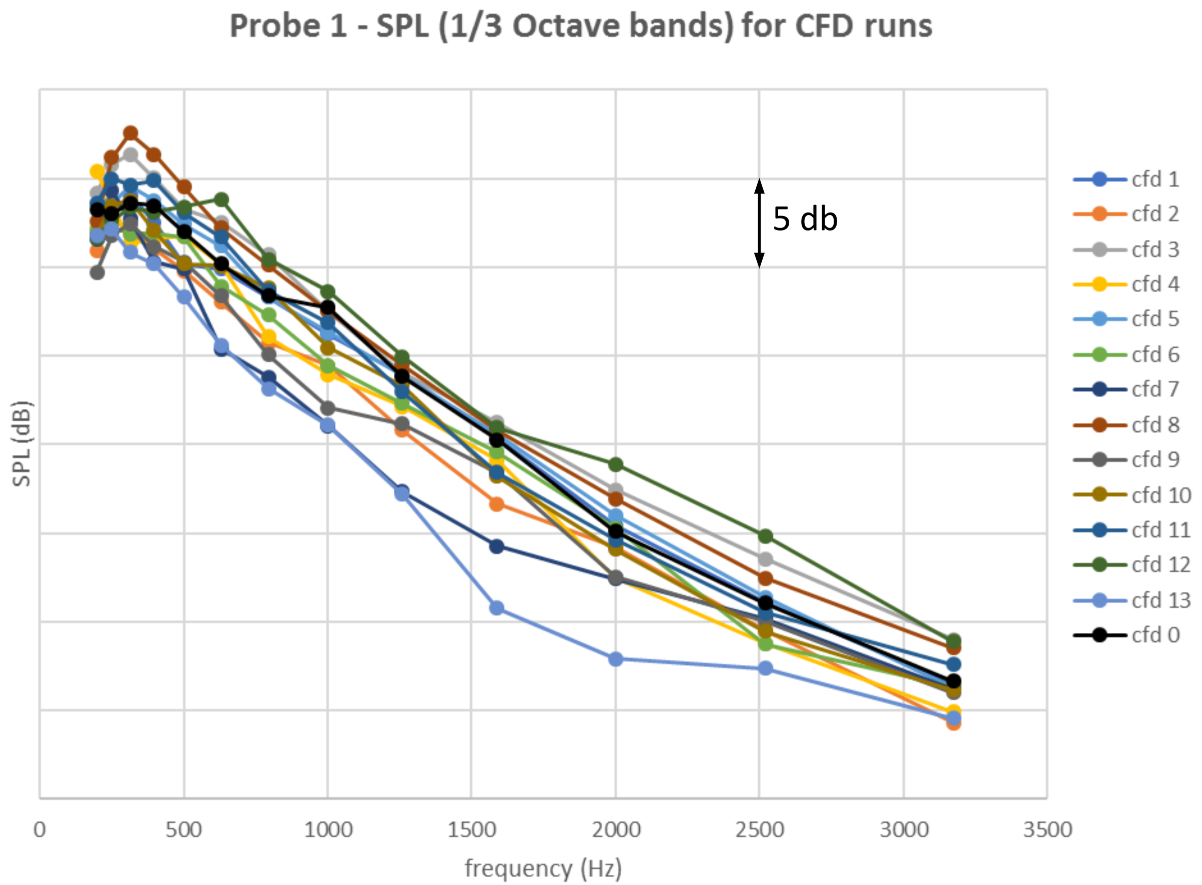
$$\boldsymbol{X}^*_{\text{geo}} = \boldsymbol{X}_{\text{geo}} + \boldsymbol{d}(\mu', \theta')$$

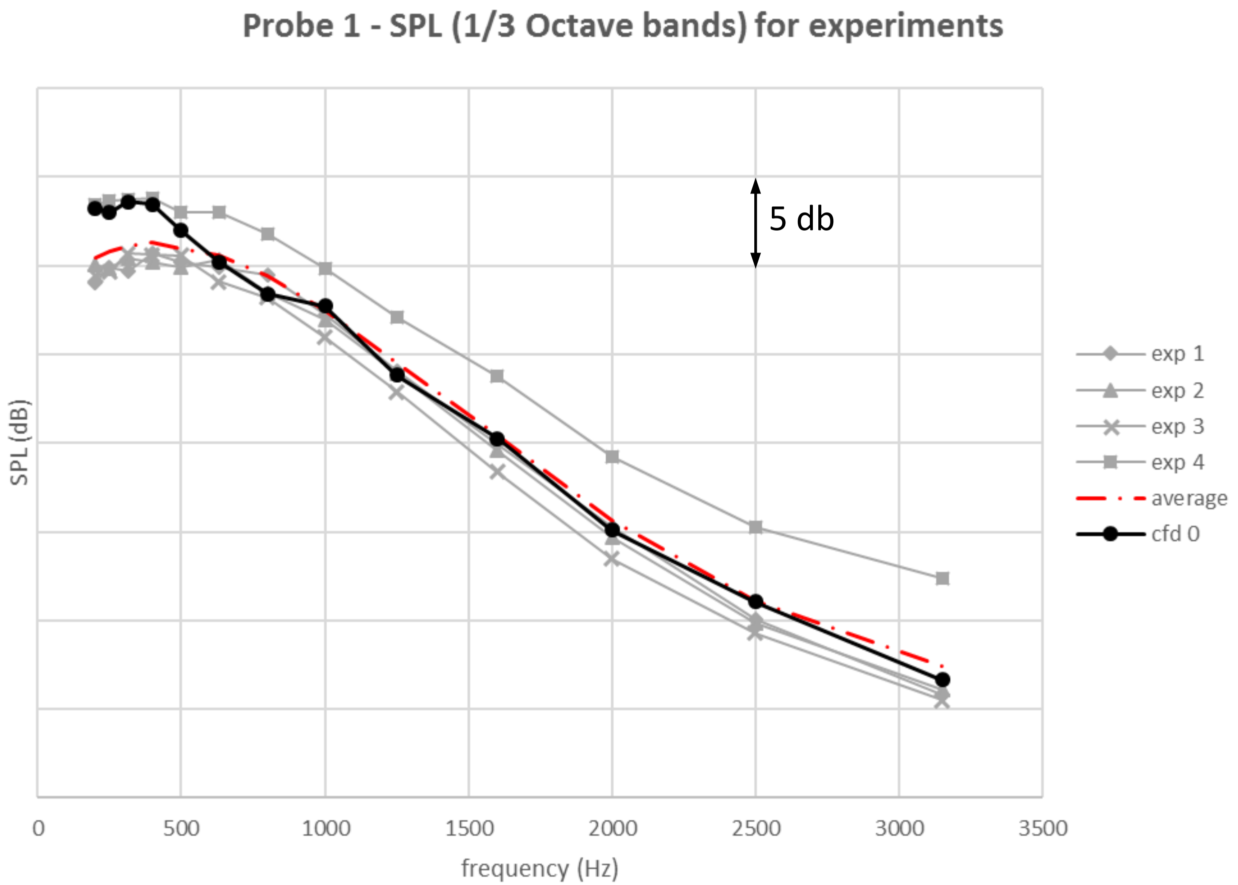
- μ' in $[-0.2, +0.2]$
- θ' in $[-0.0175$ rad, $+0.0175$ rad$]$

2 parameters

Uncertainties

- **numerical data**, obtained from 14 simulations varying the uncertainty parameters
- synthetic **experimental data**, derived from a reference automotive case with different geometry

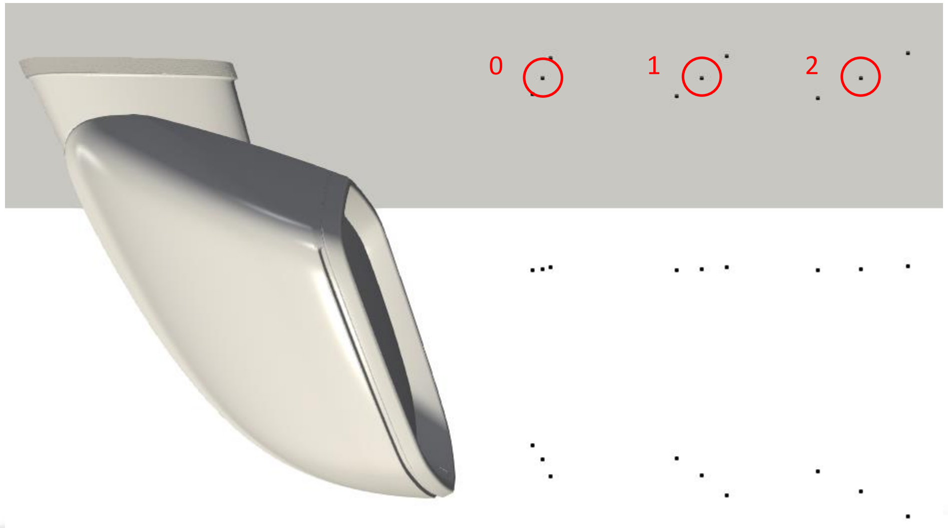


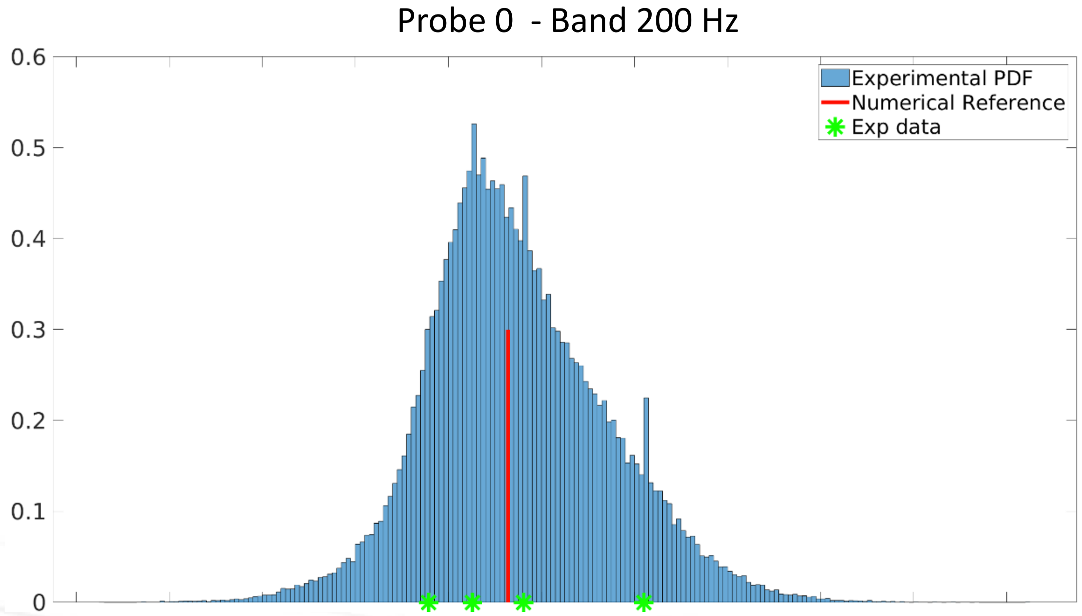


Uncertainties

Experimental Uncertainties

- Four independent samples/tests considered.
- Bootstrapping used to extract probability density functions (PDFs) from the independent samples, for some probes (see left figure)
- For each probe, spectral bands have been considered (example in right figure)





Uncertainties

Numerical Models and Uncertainties

- A model decomposition approach has been considered to model the acoustic signals

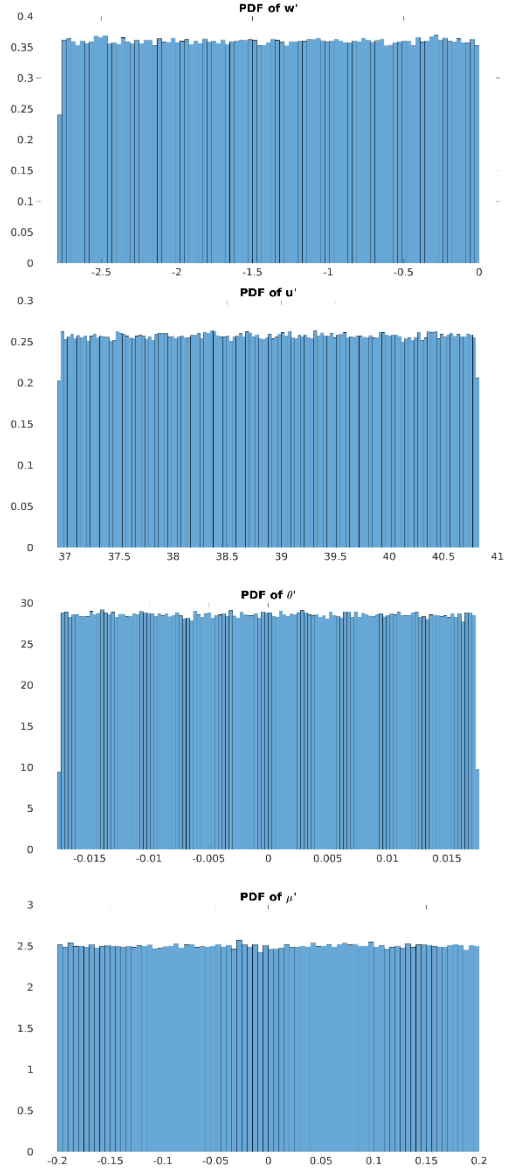
- For each probe and for each spectral band, on the basis of the numerical computations, the acoustic signal has been modelled as:

$$f(u', w', \theta', \mu') = f_0 + F_{u'}(u') + F_{w'}(w') + F_{\theta'}(\theta') + F_{\mu'}(\mu') + \cdots$$

- Models can then be used to propagate input uncertainties and quantify (characterise) output uncertainties

Uncertainties

Propagate input uncertainties through numerical models



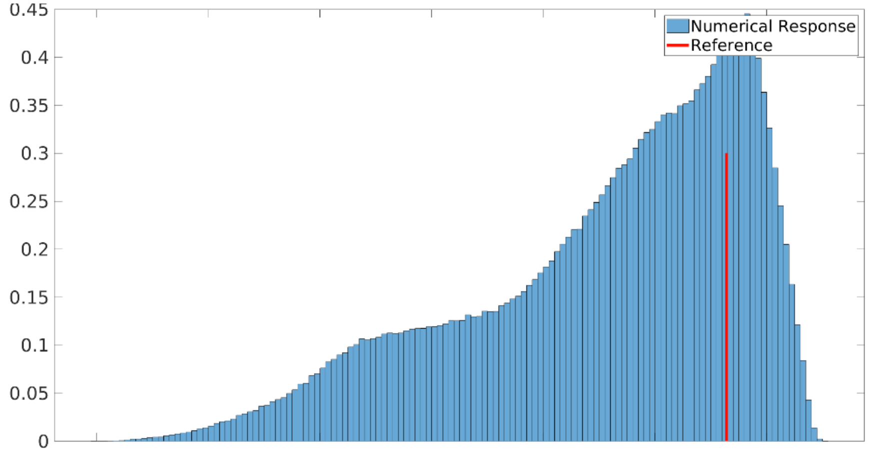
Input distributions are **uniform**

Probe 0

Band 200 Hz

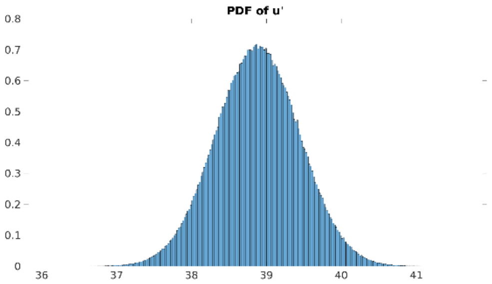
$$f(u', w', \theta', \mu')$$

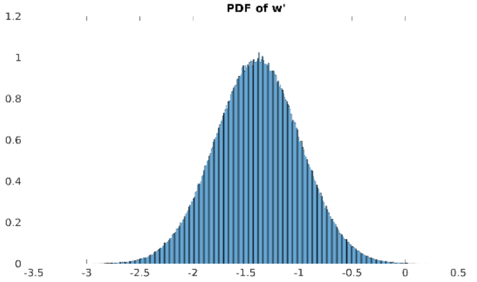
Probe 0 - Band 200 Hz

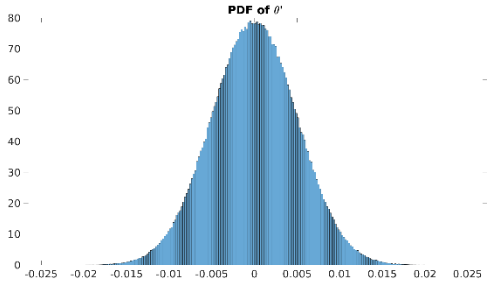


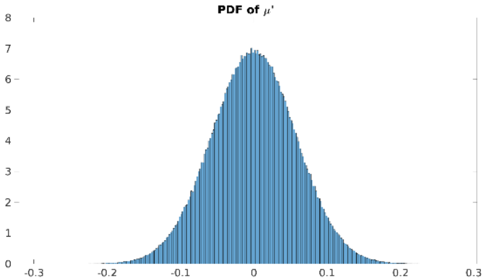
Uncertainties

Propagate input uncertainties through numerical models









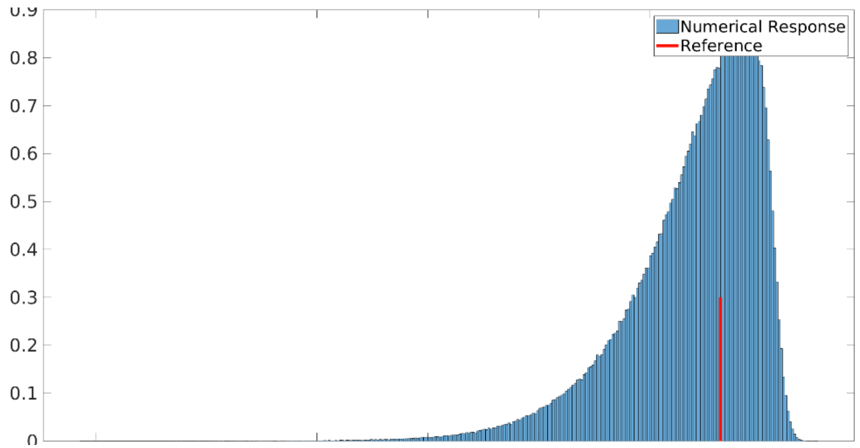
Input distributions are **Gaussians**

Probe 0

Band 200 Hz

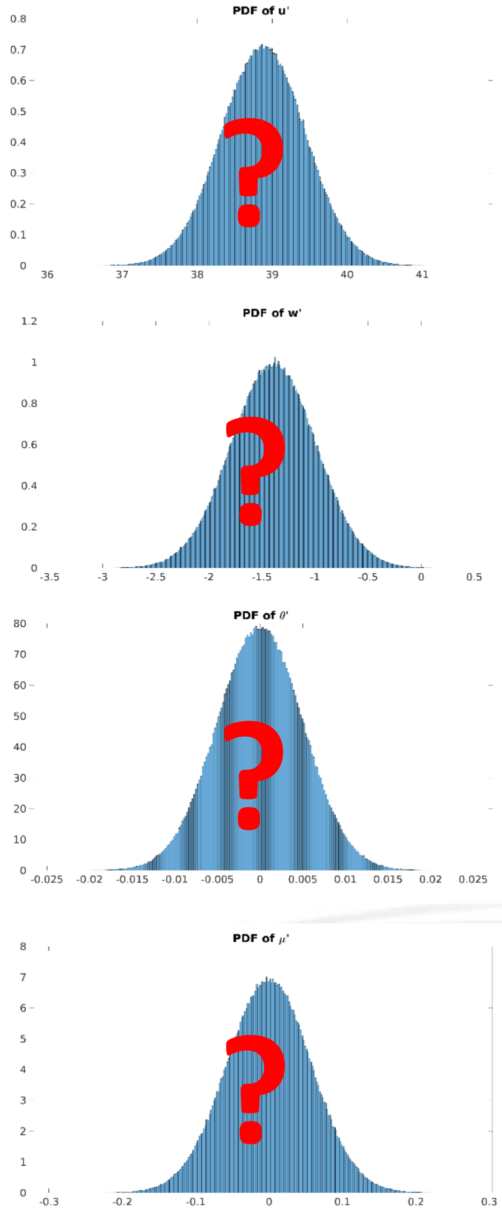
$$f(u', w', \theta', \mu')$$

Probe 0 - Band 200 Hz

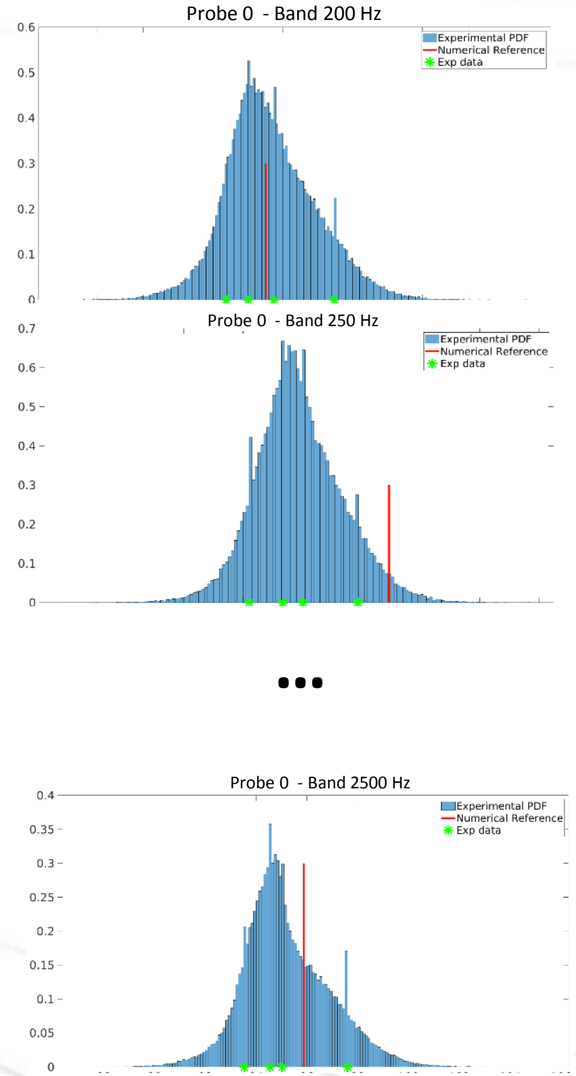


Uncertainties

By using an inverse approach, we can propagate back the experimental PDFs to detect the possible uncertainties of the tests

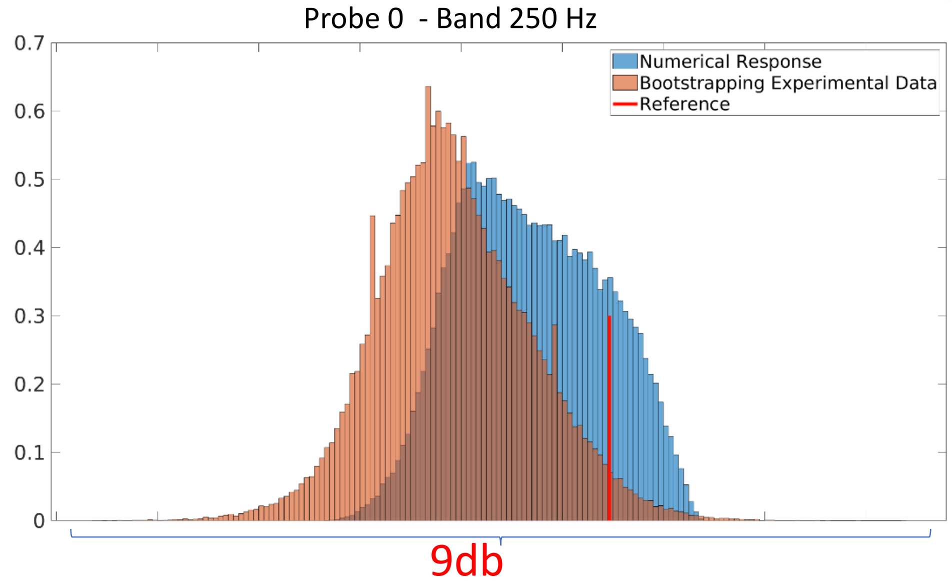


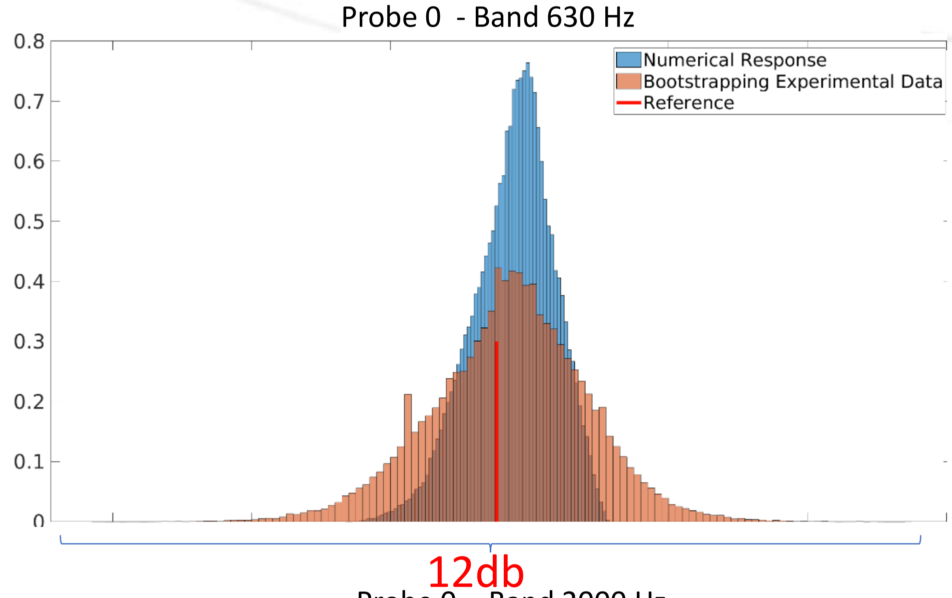
$$f(u', w', \theta', \mu')$$

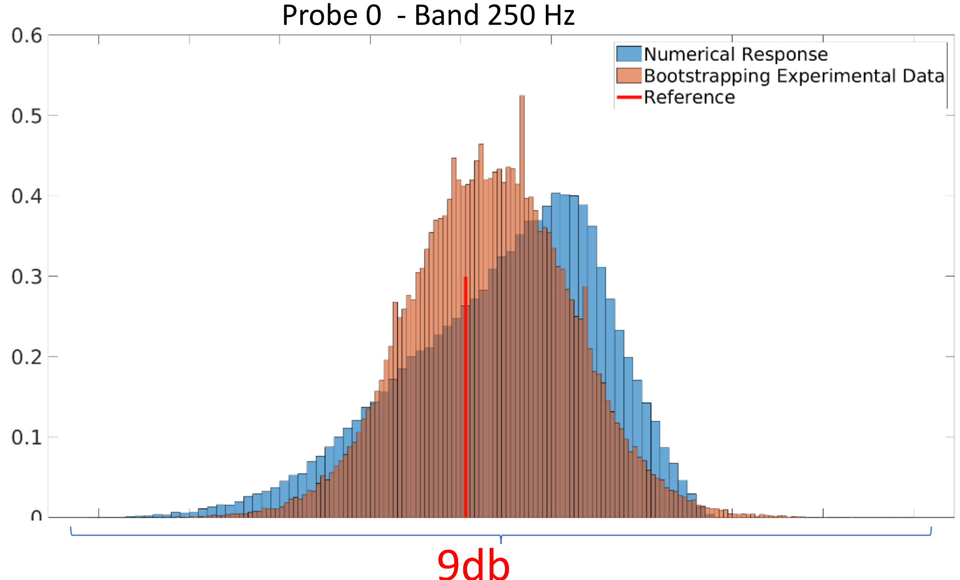


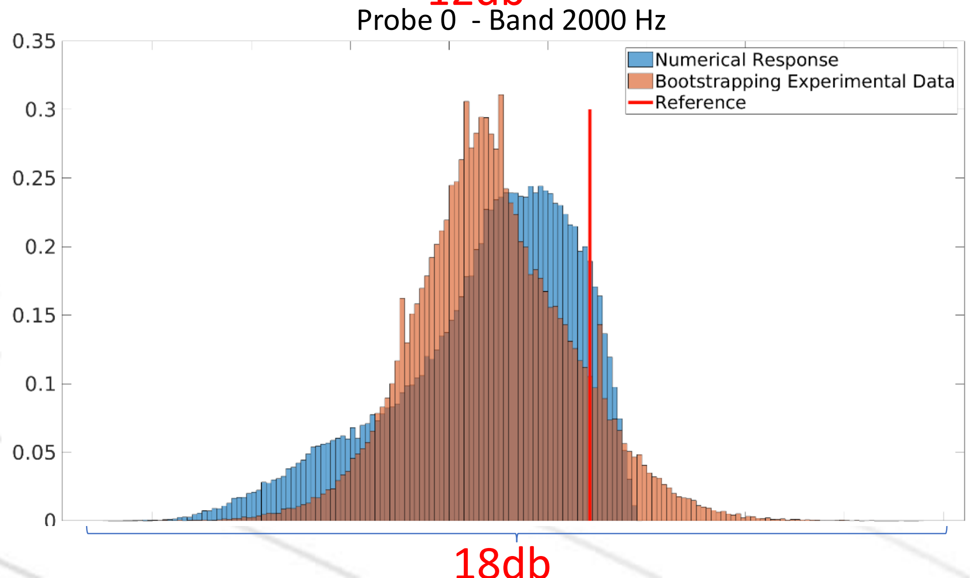
Uncertainties

By restricting the search to possible uniform distributions, we can obtain





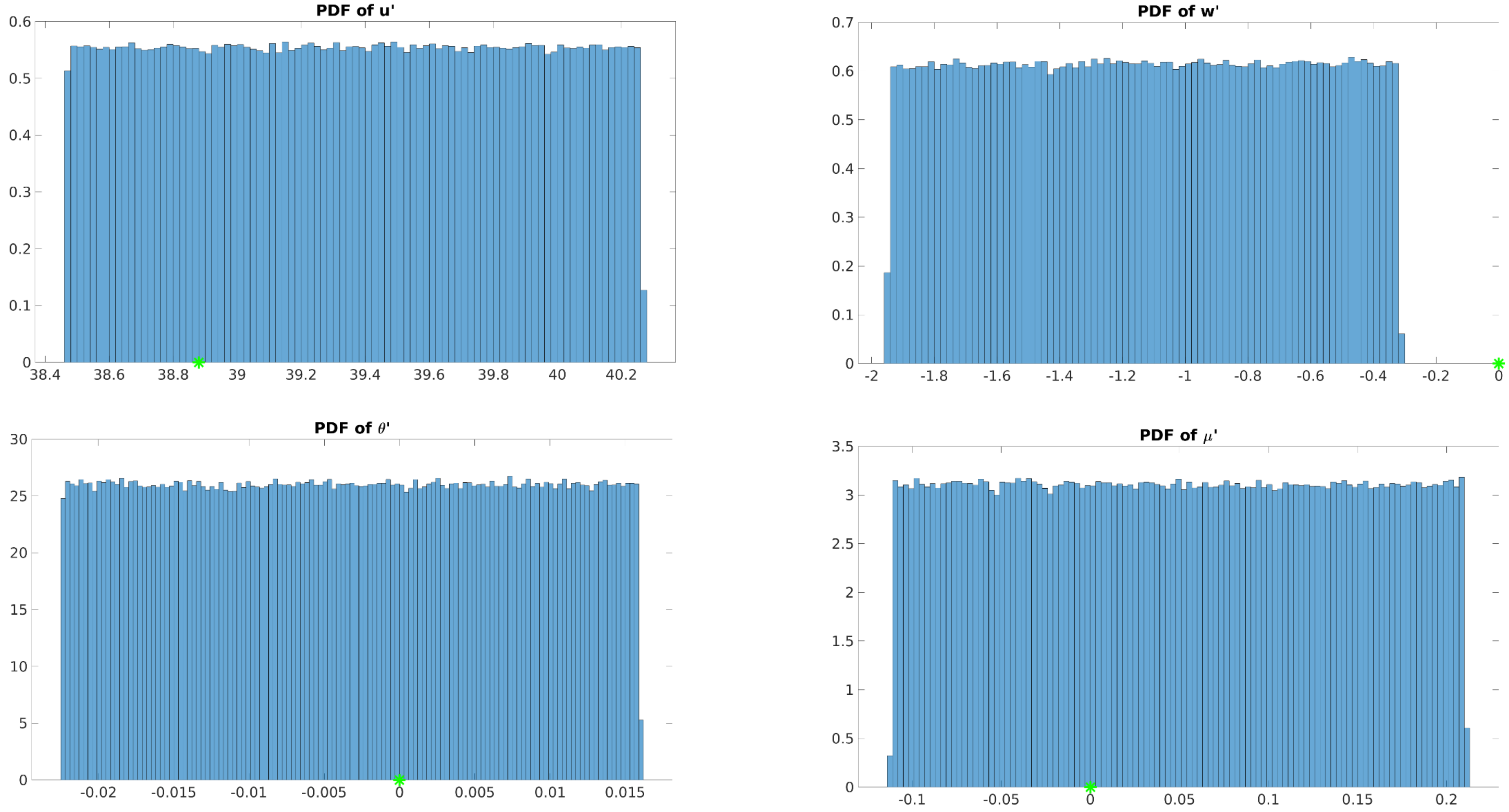




Uncertainties

By restricting the search to possible uniform distributions, we can obtain

The nominal velocity of the test was higher than expected



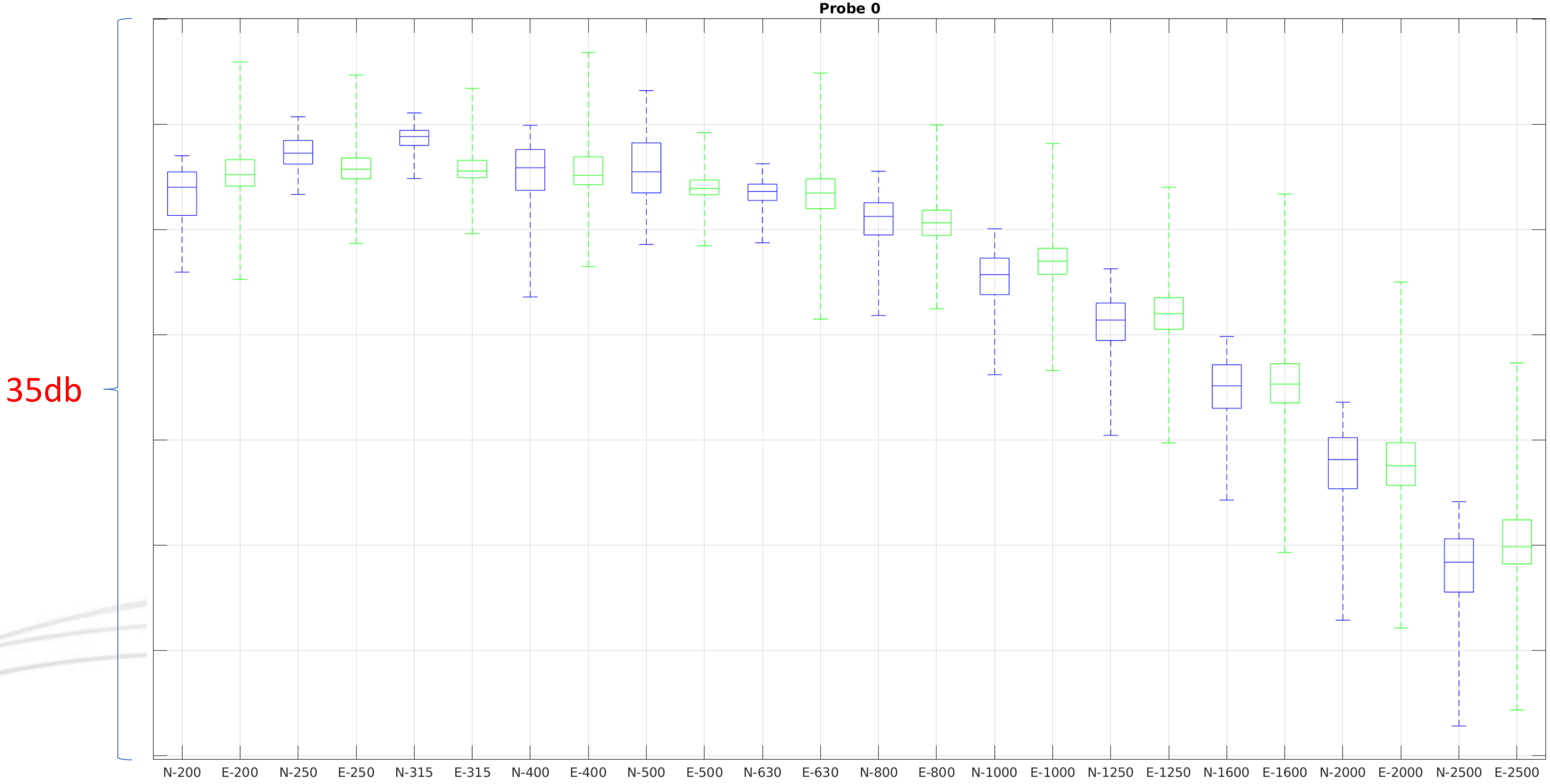
The test could be affected by some lateral wind

Quite correctly the geometry is recognised as source of uncertainty

The green point is the nominal condition

Uncertainties

By restricting the search to possible uniform distributions, we can obtain



Uncertainty Handling

Comments and Caveats

- Experimental data, synthetized from available data, do not refer to the same geometry
- More (than four) experimental repetitions would be needed for better modelling

- Uncertainty based comparison between experimental and numerical data allows for:
  - Better tuning of numerical models;
  - Better analysis of experimental data; and, then,
  - **Faster design process.**

References

Software

- OpenFOAM, the open source CFD toolbox
- mimic, computer aided surface manipulation and mesh morphing

- SMART-O2C (Strathclyde Mechanical and Aerospace Research Toolbox for Optimisation and Optimal Control)
- SMART-UQ (Strathclyde Mechanical and Aerospace Research Toolbox for Uncertainty Quantification)

https://github.com/strath-ace